iNaturalist as a tool to expand the research value of museum specimens

J. Mason Heberling[1,2,3] (iD) and Bonnie L. Isaac[1] (iD)

PREMISE OF THE STUDY: Innovative approaches to specimen collection and curation are needed to maximize the utility of natural history collections in a new era of data use. Associated data, such as digital images from the field, are routinely collected with recent herbarium specimens. However, these data often remain inaccessible and are rarely curated alongside the associated physical specimens, which limits future data use.

METHODS AND RESULTS: We leveraged the widely used citizen science platform, iNaturalist, to permanently associate field-collected data to herbarium specimens, including information not well preserved in traditional specimens. This protocol improves the efficiency and accuracy of all steps from the collecting event to specimen curation and enhances the potential uses of specimens.

CONCLUSIONS: iNaturalist provides a standardized and cost-efficient enhancement to specimen collection and curation that can be easily adapted for specific research goals or other collection types beyond herbaria.

KEY WORDS citizen science; herbarium; iNaturalist; natural history collections.

Natural history collections, especially herbarium specimens, are receiving unprecedented attention due to recently developed technologies (e.g., next-generation sequencing, niche modeling) that enable new areas of collections-based study and widespread digitization initiatives that increase their accessibility (Soltis, 2017; James et al., 2018). The diverse applications of herbarium data are rapidly evolving, especially unanticipated uses in the context of studying global change, with many specimen uses arising only recently (Heberling and Isaac, 2017). Despite this renewed appreciation of the value of existing specimens to study plant diversity across space and time in ways that would otherwise not be possible, the standard process for collecting new specimens has changed remarkably little through time. Major changes to plant collection practices in recent decades include the routine inclusion of geographic coordinates with the advent of GPS technologies and, to a lesser extent, tissue sampling for DNA analyses. Therefore, an open re-evaluation of collection methods is needed to maximize future use of herbarium data (Heberling and Isaac, 2017; Morrison et al., 2017; Schindel and Cook, 2018).

Botanists have long been aware of the potential shortcomings of herbarium specimens and the information that can be derived from them. Fogg (1940) noted that many specimens are of limited value due to poor metadata (e.g., unknown collection dates, vague localities), sparse field notes, or insufficient material to permit verifiable identification. Furthermore, some morphological characters are simply not accurately preserved in traditional dried specimens (Parnell et al., 2013). In addition to these intrinsic concerns, both known and unknown taxonomic and temporal biases are common in herbarium data (Prather et al., 2004; Daru et al., 2018; James et al., 2018). These potential shortcomings do not suggest that plant collectors a century ago were sloppy botanists and not forward thinking. Rather, technology was understandably limited, collection standards were different (e.g., presence and precision of specimen metadata), and the emerging uses of specimens today were largely unanticipated decades ago (Heberling and Isaac, 2017). Whereas innovative statistical and methodological approaches are under active development to retroactively address data gaps resulting from past collection practices and to increase the accessibility of existing data, less progress has been made to develop improved methods for new collections (Morrison et al., 2017). New approaches to plant collecting will encourage a next generation of herbarium growth, which is especially important amid alarming declines in plant collecting (Prather et al., 2004; Renner and Rockinger, 2016). Recent perspectives have re-envisioned both our very notion of what a specimen is (e.g., a traditional specimen in the context of ancillary data and other specimen types; Webster, 2017) and how to holistically approach the collecting event for next-generation collections (Schindel and Cook, 2018). However, changes to how and what

Applications in Plant Sciences 2018 6(11): e1193; http://www.wileyonlinelibrary.com/journal/AppsPlantSci © 2018 Heberling and Isaac *Applications in Plant Sciences* is published by Wiley Periodicals, Inc. on behalf of the Botanical Society of America. This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

1 of 8

specimens are collected will likely require significant financial and infrastructural support for collectors and herbaria.

Here, we introduce a practical method that utilizes the popular biodiversity-based citizen science platform iNaturalist (iNaturalist, 2018) to facilitate plant specimen collecting and curate field images alongside physical specimens, thereby augmenting their research value. Previous software applications have been developed to facilitate data capture in the field (e.g., Maya-Lastra, 2016), but none have yet been widely adopted. Although an important improvement, digital data capture in the field streamlines traditional field collection protocols but does not fundamentally improve the research value of new collections. iNaturalist provides several potential advantages as a tool for plant collectors, herbarium curators, and downstream researchers alike. The most notable of these include: (1) it is widely available (free, online resource) and externally supported (i.e., independent of herbarium- or project-specific funds); (2) it could permanently link images and other metadata collected in the field with specimen records, which is of critical practical importance, as most herbaria do not have the infrastructure to store and curate associated field images and other data beyond the physical specimen and label metadata; (3) it could connect associated observation records (which may or may not be plant taxa or physical specimen-based) to physical specimens; (4) it provides a flexible platform for an editable taxonomy and specimen identifications; and (5) it holds the potential to engage a wider community of citizen scientists in natural history collection practices.

METHODS AND RESULTS

Brief description of iNaturalist

iNaturalist is a free resource available online (https://www.inaturalist.org/) or downloaded as a mobile app (iNaturalist, 2018). Users record biodiversity observations, including date, time, location, taxonomic identification, images, audio recordings, and a countless number of other user-defined data fields. iNaturalist is a joint initiative of the California Academy of Sciences and the National Geographic Society, maintained by a dedicated staff and a community of citizen scientists (iNaturalist, 2018).

Two powerful benefits of iNaturalist are, first, the permanent integration of field images and an array of metadata linked to an observation and, second, the community-driven process for taxonomic identification and record validation. Much like museum specimens, annotation histories are a critical component of all records. When a given observation has been verified by at least two users (or reaches a greater-than-two-thirds consensus), the observation is considered relevant, accurate, and complete (i.e., suitable for sharing with biodiversity data repositories, including the Global Biodiversity Information Facility [GBIF]). iNaturalist provides algorithmic identification suggestions to its users based on visual characteristics of the uploaded images, proximity of similar records, and identification history of the taxa in question, although all identifiers are free to choose any taxon they think the image depicts. iNaturalist follows a set of established taxonomic authorities, which are updated by expert users ("Curators"). However, any user can add placeholder taxon names not currently recognized by iNaturalist. There are many parallels between these digital collections that are recorded and curated by the iNaturalist community to physical collections in herbaria curated by botanical researchers. These photographic records are essentially digital specimens that lack physical

voucher material to reference. Given the striking overlap in the data associated with iNaturalist observation-based records and those of specimen-based records, iNaturalist is well-suited as a data capture tool for plant collectors in the field.

iNaturalist as an efficient tool for plant collectors

The protocol (Appendix 1) outlined here leverages the existing infrastructure of iNaturalist to facilitate plant collecting in the field and downstream curation and data use in the herbarium. We build upon the typical process of making iNaturalist observations (see https://www.inaturalist.org/ for tutorials), with additions for making physical specimen collections and capturing the associated data. As with any museum collections, ethical and legal considerations must be taken into account to ensure necessary permits and permissions are obtained and that collecting activity will not negatively affect the plant population to be sampled. We do not describe plant collection techniques, as these protocols are detailed elsewhere (Bridson and Forman, 1998; Funk et al., 2017). Instead, we describe how to make iNaturalist observations in the context of plant collecting. See Appendix 1 for a more detailed step-by-step description.

The process (Appendix 1) starts with careful field documentation of a given individual(s) to be collected. Ideally, representative iNaturalist observations for each species in the entire community would be taken, regardless of whether physical vouchers are taken. Digital images can be taken using any camera, but the use of a GPS-enabled device (e.g., smartphone) is most efficient because geolocational information can be automatically entered when uploaded to iNaturalist. Images stored on mobile devices can be directly uploaded in the field (or later) using the iNaturalist app. Images can also be uploaded or added to existing observations at any time through the app or online. At least one image should be taken of each specimen prior to collection, but additional images from different perspectives and focusing on different plant structures are preferred and sometimes necessary. Including objects or rulers in images for scale

TABLE 1. Field names as exported from iNaturalist observations and their corresponding Darwin Core fields that are used to make specimen labels.[a]

iNaturalist field	Darwin Core field
description	verbatimAttributes[+]
habitatdwc*	habitat
localitydwc*	locality
recordNumberdwc*	recordNumber
verbatimElevationdwc*	verbatimElevation
recordedBySYMBIOTA*	recordedBy
associatedCollectorsSYMBIOTA*	associatedCollectors[+]
taxon_family_name	family
scientific_name	scientificName
observed_on	eventDate
place_country_name	country
place_admin1_name	stateProvince
place_admin2_name	county
latitude	decimalLatitude
longitude	decimalLongitude
url	associatedMedia

[a]In addition to specimen labels, these metadata are exported to their associated collections database (e.g., Symbiota data portal [Gries et al., 2014], iDigBio [www.idigbio.org]). Definitions of Darwin Core terms can be found at: http://tdwg.github.io/dwc/terms/ (Wieczorek et al., 2015).

*User-defined fields in iNaturalist created for this protocol (i.e., not default fields in iNaturalist).

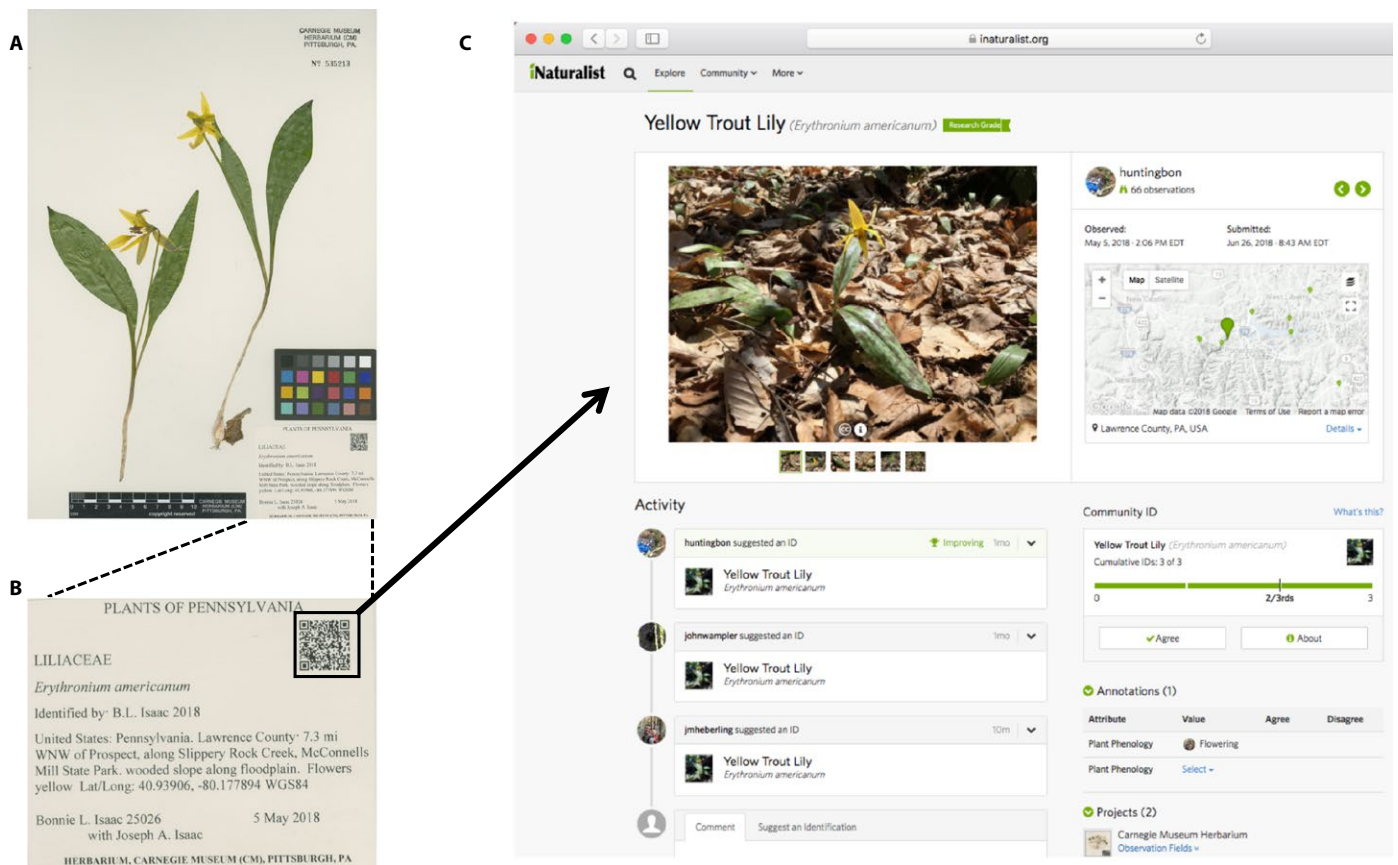[+]Following Symbiota occurrence data fields (www.symbiota.org), modified from Darwin Core.

FIGURE 1. Example herbarium specimen and its associated iNaturalist observation record. (A) Herbarium specimen (B.L. Isaac 25026; CM535213) of *Erythronium americanum* Ker Gawl. (Liliaceae). (B) Close up of herbarium specimen label that includes standard core metadata plus a QR code to directly connect users to the associated iNaturalist observation data. These QR codes can be scanned with any smart device (e.g., tablet computer or smartphone), which automatically opens the online record in the device's internet browser. (C) The iNaturalist observation record associated with this herbarium specimen (https://www.inaturalist.org/observations/13798754), which includes not only the digital metadata on the specimen label but also other ancillary data such as in situ color images taken at time of collection, a map illustrating the specimen's location (which can be explored further for associated observations), crowdsourced phenology status, and the complete identification history and other comments by the iNaturalist community of citizen scientists.

can be helpful for reference. Traditional specimens are collected following standard methods (Bridson and Forman, 1998), which may also include tissue samples for genomic studies (Funk et al., 2017). iNaturalist observations with associated physical vouchers are added to a "Project" in iNaturalist to facilitate necessary data entry and downstream curatorial tasks of printing specimen labels and exporting data to relevant specimen databases. iNaturalist "Projects" are easily set up online (https://www.inaturalist.org/). We recommend each herbarium (or plant collector) design its own Project to suit its needs, being sure to include necessary user-defined fields that are not already part of the core iNaturalist data fields (e.g., collector number; see Appendix 1). Data fields in iNaturalist can easily be adapted to follow Darwin Core data standards for biodiversity data (Wieczorek et al., 2012), which facilitate data exported from iNaturalist to local or online collections databases (Table 1).

Connecting herbarium specimens to iNaturalist data

Through the use of "Projects" in iNaturalist, metadata for specific observations (Table 1) are exported to print herbarium labels and merged into relevant collections databases. In addition to permanently archiving the corresponding iNaturalist record number (URL; Table 1) in the collections database (via Darwin Core field: "associatedMedia"), we also include this web link on the physical specimen label in the form of a Quick Response Code (QR code). QR codes are two-dimensional barcodes that require less space than traditional barcodes. Many smart devices with cameras (e.g., tablet computers, smartphones) have built-in QR readers. For those devices that do not have built-in QR readers, several software options are free and widely available for download. We use QR codes on specimen labels to store the URL for the associated iNaturalist observation record. In this way, herbarium users examining a specimen can scan the label to be instantly directed to additional information, including field images (Fig. 1). Similarly, herbarium users can search online specimen data portals for specimens associated with iNaturalist images through the Darwin Core field "associatedMedia." We recommend using this data field to archive the iNaturalist URLs as a standard component of specimen metadata. An example data set (Appendix S1) and a Microsoft Word template (Appendix S2) for making herbarium labels from iNaturalist data are available in the Supporting

Information and described in Appendix 1. Our approach could also be extended to previously collected and historic specimens to retroactively link archived field images and notes that may already exist.

Benefits for collections-based research

First, and perhaps most notably, our approach leverages the existing infrastructure of iNaturalist to connect specimens to images from the field (Fig. 1). Many plant traits may not be well represented in dried specimens (e.g., Fogg, 1940; Parnell et al., 2013) but are well documented with high-resolution digital images (Table 2). In the example in Fig. 1, anther color, degree of mottling on leaves, flower angle, habitat, and population-level attributes are captured in the iNaturalist record but are lacking on the herbarium specimen. Field images provide additional information that varies by species. The taxonomic or ecological significance of many of these image-derived traits is currently unknown. In addition to plant traits, iNaturalist also provides ecological and environmental context, which, to date, is infrequently and inconsistently recorded with existing specimens (e.g., habitat and/or associated species on herbarium labels). Second, this approach provides a platform to search for related regional observations as well as other observations that were recorded in the same locality and/or on the same collection date. Third, the integration of physical specimens with iNaturalist observations engages a community of citizen scientists for the curation of specimen metadata, including taxonomic identification and phenological scoring.

Practical benefits for plant collectors and herbarium curators

The use of iNaturalist as a tool for plant collectors and herbarium staff has several logistical advantages, saving time and improving data quality. First, the use of iNaturalist by plant collectors is a time-efficient and accurate method for digital data capture in the field. If using a GPS-enabled camera (e.g., smartphone), latitude and longitude information is automatically included with uploaded image(s). To date, however, elevation is not automatically recorded by iNaturalist, but can easily be included using the built-in or other mobile device apps (see Appendix 1). Taxonomic identification is facilitated by artificial intelligence features in iNaturalist, the iNaturalist community, and a community-curated taxonomic nomenclature. iNaturalist improves efficiency and accuracy for botanists relative to field guides or memory alone by providing a list of identification suggestions and a set of pre-defined taxonomic names from which to choose (e.g., avoid misspellings, taxonomic synonyms). Accuracy is also improved with identification suggestions or verifications from other iNaturalist users. Second, once observations are complete, these data can be easily exported and directly converted into herbarium labels and merged into collections databases. The use of iNaturalist "Projects" permits plant collectors to directly share data with herbarium staff (including localities of rare species that may be censored to the general public). Data quality is also improved by providing a standardized set of required or suggested data fields for all new vouchers being deposited, which is especially useful for outside consultants or amateur botanists who are new to plant collecting or infrequently deposit specimens. Finally, this method effectively expands the collection event to include both specimen-based and observation-based records across and within taxonomic groups. For instance, multiple observations of different individuals of the same population can be made to document variation beyond

TABLE 2. Biological information that may not be well preserved in traditional dried, pressed herbarium specimens but that is well represented in digital photographs associated with same specimens in situ. These include individual plant characteristics (phenotype) and site-, population-, and community-level information. Additional information provided by these images can be used in specimen identification, as well as many other research applications, including taxonomy and ecology.

Biological information	Example(s)
Individual plant level	
Color	Color of reproductive structures (e.g., petals, anthers, etc.), leaves, etc.
Bark	Furrowing or lenticels in bark
Arrangement of stems	Orientation, angle, and/or attachment pattern of stems
Leaf angle	Orientation and angle of leaves in situ
No. of stems	Single main stem vs. several stems
Size	Relative plant height and size of large structures that do not fit on standard herbarium sheet
Habit/posture	Rigidity of plant (e.g., upright, trailing, or prostrate)
3D morphology	Architecture or shape of entire plant or plant part (e.g., inflorescence)
Ephemeral structures	Short-lived or delicate plant structures (e.g., petals, needles abscise or lost upon collection)
Population-, community-, and site-level	
Habitat	Ecosystem type (e.g., forest understory, field, roadside), soil substrate, light environment
Associated species	Co-occurring plant taxa
Abundance	Population density at microsite-level
Phenological variation	Intraspecific variation in flowering status of population (i.e., are all individuals flowering?)
Pests	Presence of herbivory and/or herbivores
Pollinators	Presence of pollinators

one or several "duplicate" specimens. This approach provides a realistic, cost-efficient approach to "holistic" sampling (Schindel and Cook, 2018). Although physical specimens are preferred, this approach serves as a compromise in an era of increasing financial and time constraints on collections staff and botanists.

CONCLUSIONS

Herbarium specimens are the necessary gold standard as primary data for any botanical study (Culley, 2013), but to date, most vouchers consist of a physical specimen and a limited set of core metadata. Given the recent diversification of specimen uses, new approaches are necessary to foster the next generation of collections-based research (Schindel and Cook, 2018) and maximize future data use (Morrison et al., 2017). The value of specimens is substantially enhanced when they are considered in the broadest sense to include other specimen types and ancillary data to capture as much genotypic and phenotypic information possible (Webster, 2017). The addition of including field images alongside physical specimens, as presented in the current protocol, is one realistic step toward this goal. New specimens rarely include digital field images; or, if they do, these images remain inaccessible because most herbaria do not have the infrastructure to curate these digital data alongside voucher specimens. Using the popular biodiversity data platform iNaturalist, our protocol improves the efficiency and accuracy of specimen collection in the field, facilitates downstream curatorial tasks (i.e., label making, metadata digitization and export to accessible databases),

and expands the value of herbarium specimens through direct connection to associated iNaturalist observation data and field images.

A potential concern of our protocol is the unknown future of iNaturalist, the data stored therein, and the stability of iNaturalist observation URLs. These concerns are similar to those currently faced by all digital biodiversity databases, and to a lesser extent, even herbaria. We argue that published uses of iNaturalist will enable continued development and long-term support for this important biodiversity resource. Furthermore, it is important to note that our protocol utilizes iNaturalist as a tool to facilitate collections and enable research but also requires specimen data to be housed in herbarium databases for long-term curation and storage. Online herbarium collection data portals (e.g., Symbiota-based) have functionality to include field images, and future developments should include the automatic retrieval of images from iNaturalist for permanent storage in herbarium databases to protect against data loss. Future developments are needed to seamlessly connect iNaturalist with natural history collections databases and vice versa.

Despite the growing roles for natural history collections to address a range of basic scientific and societal challenges in an era of rapid environmental change, plant collecting is in decline (Prather et al., 2004). Observation-based occurrence records have rapidly increased in recent years, far outpacing verifiable specimen-based records (Troudet et al., 2018). These trends may represent a cultural shift by the scientific community, or simply be due to temporal and financial constraints. It has been argued that traditional methods of specimen collection are outdated, unethical, and can be replaced by nonlethal sampling techniques (e.g., photographs, tissue samples; Minteer et al., 2014). However, it is clear that physical vouchers are necessary for verifiability, species conservation, and to enable future research (Culley, 2013; Funk et al., 2018). Traditional specimens must remain the core of biological collections but should be viewed in a broader context of data types, augmented with photographic and related metadata to maximize future research (Webster, 2017). Although our protocol provides an important improvement to specimen collection, ongoing discussion by the broader scientific community is needed for developments to standardize all aspects for the next generation of natural history collections, from the collecting event (e.g., what and how to collect?) to the logistics of capturing and curating associated specimen-derived data. Although it is designed for herbarium use, our flexible approach using iNaturalist can be extended to other types of natural history collections and has the potential to invigorate a new vision for the next generation of collections-based research.

ACKNOWLEDGMENTS

AUTHOR CONTRIBUTIONS

J.M.H. conceived and designed the study, B.L.I. developed the label protocol, both authors contributed to writing.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information section at the end of the article.

APPENDIX S1. Example data set of iNaturalist observations to demonstrate protocol to make herbarium labels.

APPENDIX S2. Template with macros enabled (Microsoft Word) to automatically generate herbarium labels with QR codes from observation records directly exported from iNaturalist.

LITERATURE CITED

Bridson, D. M., and L. Forman. 1998. The herbarium handbook, 3rd ed. Royal Botanic Gardens, Kew, Richmond, Surrey, United Kingdom.

Culley, T. M. 2013. Why vouchers matter in botanical research. *Applications in Plant Sciences* 1: 1300076.

Daru, B. H., D. S. Park, R. B. Primack, C. G. Willis, D. S. Barrington, T. J. S. Whitfeld, T. G. Seidler, et al. 2018. Widespread sampling biases in herbaria revealed from large-scale digitization. *New Phytologist* 217: 939–955.

Fogg, J. 1940. Suggestions for collectors. *Rhodora* 42: 145–157.

Funk, V., M. Gostel, A. Devine, C. Kelloff, K. Wurdack, C. Tuccinardi, A. Radosavljevic, et al. 2017. Guidelines for collecting vouchers and tissues intended for genomic work (Smithsonian Institution): Botany Best Practices. *Biodiversity Data Journal* 5: e11625.

Funk, V. A., R. Edwards, and S. Keeley. 2018. The problem with(out) vouchers. *Taxon* 67: 3–5.

Gries, C., E. E. Gilbert, and N. M. Franz. 2014. Symbiota: A virtual platform for creating voucher-based biodiversity information communities. *Biodiversity Data Journal* 2: e1114.

Heberling, J. M., and B. L. Isaac. 2017. Herbarium specimens as exaptations: New uses for old collections. *American Journal of Botany* 104: 963–965.

James, S. A., P. S. Soltis, L. Belbin, A. D. Chapman, G. Nelson, D. L. Paul, and M. Collins. 2018. Herbarium data: Global biodiversity and societal botanical needs for novel research. *Applications in Plant Sciences* 6: e1024.

Maya-Lastra, C. A. 2016. ColectoR, a digital field notebook for voucher specimen collection for smartphones. *Applications in Plant Sciences* 4: 1600035.

Minteer, B. A., J. P. Collins, K. E. Love, and R. Puschendorf. 2014. Avoiding (re) extinction. *Science* 344: 260–261.

Morrison, S. A., T. S. Sillett, W. C. Funk, C. K. Ghalambor, and T. C. Rick. 2017. Equipping the 22nd-century historical ecologist. *Trends in Ecology and Evolution* 32: 578–588.

iNaturalist. 2018. iNaturalist [online]. Website https://www.inaturalist.org [accessed 29 July 2018].

Parnell, J., T. Rich, A. McVeigh, A. Lim, S. Quigley, D. Morris, and Z. Wong. 2013. The effect of preservation methods on plant morphology. *Taxon* 62: 1259–1265.

Prather, L. A., O. A. Fuentes, M. H. Mayfield, and C. J. Ferguson. 2004. The decline of plant collecting in the United States: A threat to the infrastructure of biodiversity studies. *Systematic Botany* 29: 15–28.

Renner, S. S., and A. Rockinger. 2016. Is plant collecting in Germany coming to an end? *Willdenowia* 46: 93–97.

Schindel, D. E., and J. A. Cook. 2018. The next generation of natural history collections. *PLoS Biology* 16: e2006125.

Soltis, P. S. 2017. Digitization of herbaria enables novel research. *American Journal of Botany* 104: 1281–1284.

Troudet, J., R. Vignes-Lebbe, P. Grandcolas, and F. Legendre. 2018. The increasing disconnection of primary biodiversity data from specimens: How does it happen and how to handle it? *Systematic Biology* https://doi.org/10.1093/sysbio/syy044.

Webster, M. 2017. The extended specimen. *In* M. Webster [ed.], The extended specimen: Emerging frontiers in collections-based ornithological research, 1–9. CRC Press, Boca Raton, Florida, USA.

Wieczorek, J., D. Bloom, R. Guralnick, S. Blum, M. Döring, R. Giovanni, T. Robertson, and D. Vieglais. 2012. Darwin Core: An evolving community-developed biodiversity data standard. *PLoS ONE* 7: e29715.

Wieczorek, J., M. Doring, R. De Giovanni, T. Robertson, and A. Antonelli. 2015. Darwin Core terms: A quick reference guide [online]. Website http://rs.tdwg.org/dwc/terms/ [accessed 1 August 2018].

APPENDIX 1. Detailed protocol for making herbarium labels from iNaturalist records.

The protocol below outlines how to use iNaturalist as a tool to facilitate and augment traditional herbarium specimen collection practices in the field. Specific steps are subject to change based on iNaturalist updates and other developments.

A. The collecting event: Associating new collections with an iNaturalist observation

The following section briefly outlines the process of making an iNaturalist observation alongside traditional specimen collections. A description of general herbarium methodology is detailed elsewhere (e.g., Bridson and Forman, 1998; Funk et al., 2017).

1. Creating an iNaturalist account—iNaturalist is a free naturalist app for identifying and documenting observations of life. iNaturalist can be accessed online via a browser or through free mobile device apps. See https://www.inaturalist.org/ for further information and instructions to create an account and upload observations.

2. Creating a project in iNaturalist—Information on "Projects" can be found at the iNaturalist website (https://www.inaturalist.org/). iNaturalist Projects function to collate observations for specific purposes (e.g., BioBlitzes, tracking species of interest, monitoring specific localities). There are multiple types of projects, each with different functions. Here, we use Projects to connect iNaturalist records with physical specimen records via additional observation fields. For our purposes, we use what iNaturalist refers to as a "Traditional Project," which allows the use of custom observation fields and manually added individual observations. These projects can currently be created here: https://www.inaturalist.org/projects/new. We recommend that each herbarium (or individual plant collector) create a Project for their own use. Although making a project is not required, using this feature allows users to: (1) easily filter only observations of interest for data export, (2) make customized data fields associated with a specimen automatically pop up for entry either in the field (on smart device) or on your computer, and (3) enable herbarium collection managers or curators to invite users to "join" the project to facilitate the transfer of detailed metadata (label information and images) with newly deposited specimens into the relevant herbarium collection. This also enables collection managers the ability to edit records, if needed. Projects can be "invite-only" in order to avoid other users adding to your project. Invitations can also be sent to users who wish to deposit specimens. If Projects are left "open," any observations inappropriately added can be removed from the Project by managers.

We use the project "Carnegie Museum Herbarium" (https://www.inaturalist.org/projects/carnegie-museum-herbarium) in this protocol for demonstration purposes. The specifics of the project can be adapted for individual uses. For instance, a Project can require a set of user-defined fields for each observation before being added.

3. Creating iNaturalist observation records—Before collecting a plant specimen, we recommend taking several pictures. The ideal number and type of photographs will vary depending on taxon and context. Although not necessary, taking photos on a GPS-enabled device (e.g., smartphone) is strongly recommended. Elevation can be acquired using a variety of smartphone apps, GPS units, or inferred at a later point based on geolocality. We suggest using a smartphone app that stamps the geolocality information and elevation on images, such as the Theodolite app available for iOS devices (Hunter Research and Technology LLC, http://hrtapps.com/). At least one (preferably several) photograph(s) should be taken from multiple perspectives. Ideally, these photographs should be sufficient to identify the plant species, although for some taxa this may not be possible. Take several images in the field, including close ups of the reproductive structures (if present), leaves (including basal leaves if different), as well as photos that convey the general habitat, the local distribution and abundance of the population, phenophase, and associated species and abiotic conditions. Objects of known dimensions (e.g., coin) or a ruler in the same plane as focal plant structures can be included for scale. Including a color reference may also be useful. Lastly, we emphasize the importance of ensuring the photograph(s) are of the individual(s) collected. Photographs from the field and other metadata (Table 1) can be uploaded at the time of collection in the field using a smart device (e.g., smartphone or tablet, depending on cellular service or wireless signal) or at a later point using your smart device or computer.

Most metadata are automatically recorded by iNaturalist. Core locality data (e.g., GPS coordinates, country, state, county) are automatically added to the record if pictures were taken using a GPS-enabled device such as a smartphone. We also recommend adding a detailed locality description (e.g., municipality name and other stable landmarks separated by commas) for labels and in the event GPS coordinates are incorrect. Plant family is also added automatically, following the identification to genus or species. Additional metadata should be added to each iNaturalist observation individually or can be edited in bulk using the "Batch edit" function. Batch editing can be done by clicking on "Edit observations" at the upper right of the screen when you are signed into your account at https://www.inaturalist.org/. This feature may be especially helpful when adding metadata to observations from the same locality (e.g., apply the same locality description to many records at once). Newly defined data fields can be added in iNaturalist, depending on specific needs. At minimum, we recommend completing the data fields listed in Table 1.

We strongly recommend recording and uploading all observations in a sampled community, regardless of whether each iNaturalist observation was also physically collected. However, only those iNaturalist records that directly link to a physical specimen should be added to the Project in iNaturalist, as only these records will need a label printed (described below).

Although physical specimens are preferred, there are many reasons that may constrain the number of specimens that can be collected (e.g., ethics, time, cost, space, phenophase). Making as many iNaturalist observations as possible in the community will maximize future use of the subset of records that were physically collected.

B. Post-collection processing: Exporting iNaturalist data

1a. Exporting data from iNaturalist (within a "Project")—Open iNaturalist at https://www.inaturalist.org/home. Under the

"Community" tab at the top of the webpage, choose "Projects," select "Carnegie Museum Herbarium" (or your Project), partway down on the right select "Export Observations," csv, and choose the selections for which you wish to make labels. Sorting by date or observer will be helpful to locate records of interest for download.

Once you are on the "Export Observations" screen, choose the columns you want to export. Choose the "all" option under "Basic," "Geo," "Taxon," "Taxon Extras," and "Observation Fields." It is easiest to simply export all columns to be sure the necessary fields are included in your data file. Then click "Create Export." Once the export is complete, download the .csv file and open in Excel. Save the file as an Excel file (.xlsx).

1b. Exporting data from iNaturalist (outside of a "Project")—Open iNaturalist at https://www.inaturalist.org/home. Open either the "Explore" or "Your Observations" tab at the top, in the top right-hand corner select "Filters" and choose the selections for which you wish to make labels. Once you make your selection, you may need to select the filters option again to have the filters box pop up. The bottom right of the filters screen has a download option. Click on "Download."

Once you are on the "Export Options" screen, choose the columns you want to export. Choose the "All" option under "Basic," "Geo," "Taxon," "Taxon Extras," and "Observation Fields." Then click "Create Export." Once the export is complete, download the .csv file and open in Excel. Save the file as an Excel file (.xlsx).

Note that observations with a geoprivacy of "obscured" or "private" (e.g., sensitive species) will not export with coordinates unless you are a project curator, you uploaded the record, or otherwise have access.

C. Post-collection processing: Generating herbarium labels from iNaturalist data

The instructions below use a sample iNaturalist data set (see Appendix S1) and an associated blank template for generating herbarium labels (Appendix S2) similar to that shown in Fig. 1B. This section of the protocol was written using Microsoft Word 2016 and Windows 7 Professional. Appendix S2 and the associated protocol steps below can be adapted for other word processors (e.g., LibreOffice) and operating systems.

1. Downloading a QR code generator for your word processing software—Before you can make QR codes on labels you must have QR4Office add-in installed in your Microsoft account. Make sure you are logged into your Microsoft account. Visit store.office.com. Search for QR4Office add-in. Add this free add-in to your office account.

Unfortunately, the QR4Office add-in is not available for Word for Mac at the time of the publication of this protocol. However, it can be used in Office Online on any operating system and other software for generating QR codes are available. This protocol uses QR4Office because it is free, widely available, and designed for Microsoft Word.

2a. Generating herbarium labels with QR codes using iNaturalist data (using example label template)—Follow these instructions to create labels using the blank label template provided as Appendix S1: Open the Microsoft Word document with macros enabled (.docm; Appendix S2). Under the "Mailings" tab choose "Select Recipients" then "Use an Existing List." Next, search for and select the Excel file

with your iNaturalist data (see Appendix S1 for example data file). Open this file by clicking "Open" in the dialog box. Then select the table again and click OK.

Next, select "Preview Results" to see the QR codes on herbarium labels. You can then select "Finish & Merge, Edit Individual Documents." You may now edit these labels if needed before printing your labels.

2b. Generating herbarium labels with QR codes using iNaturalist data (*create your own label template in Word)—Follow these directions to create your own label template in Word: Open a new Word document and save it. Select the "Mailings" tab. Choose "Select Recipients" then "Use an Existing List." Search for the Excel file you exported from the iNaturalist or use Appendix S1. Open this file using the dialog box that appears, choose the table, and click OK.

While in the "Mailings" tab, select "Start Mail Merge," choose labels, then select "Details." Adjust the label height, label width, number of labels across and number of labels down. You may have to also adjust the vertical and horizontal pitch. If you set these to zero, they will autofill with the height and width that you set the labels. You should now have a document divided into labels.

You can now type in any title headers or field names to be added to the label. Select the area of the label where you would like each field placed. In the "Mailings" tab, select "Insert Merge Field." Select the field that you would like to place on the label. Using the "Insert Merge Field" option, you can place all the fields you wish on your label. To insert the QR Code, press Ctrl F9, which will bring up these brackets: {}. You must use Ctrl F9 to make these brackets; typing them will not work. Inside these brackets, you will need to type the following exactly: {MERGEBARCODE url QR \h 1 \q L}. Pay special attention to capitalization and spacing. Replace the letters "url" with the URL you wish to use for the QR code (i.e., web link to iNaturalist record). This field in iNaturalist is called "url" (Table 1).

Once you have this coding in your document, you can click "Preview Results" to see the URL code. While in Preview Results, right click on the URL code and select "Edit Barcode." This popup box will have an "Advanced" button on the bottom left. Choose the "Advanced" button. Here, you can change the size of the QR code with the scaling percent under "Size and Rotation."

Once you have the fields on the label where you would like them, you can adjust coding for some of the fields. The date field in iNaturalist is exported in an ambiguous format (e.g., 6/7/2018). To avoid ambiguity, it is preferable for the month name to be spelled out. To change the format of the date on the label, select the date field (observed_on in iNaturalist), right click, and select "Toggle Field Codes." After the name of the field inside the brackets, type in \@ "d MMMM yyyy". Once again, pay special attention to capitalization and spacing. You should have {MERGEFIELD observed_on \@ "d MMMM yyyy"}. Remember to include the quotation marks around "d MMMM yyyy". You may also like to adjust how the latitude and longitude fields display and print. Output from iNaturalist uses 15 places after the decimal point as a default. To limit the number of places after the decimal point, once again select the field on the label, right click, and choose "Toggle Field Codes." Inside the brackets after the field name type \# #.00000. The number of zeros that you place after the decimal point are the number of digits that will show on the label. Your coding should look like this: {MERGEFIELD latitude \# #.00000}. Follow the same procedure for longitude.

Because iNaturalist does not show which datum is being used for their data, you will need to type WGS84 or whatever datum you may be using on the label form so that it prints on the labels. (Note: iNaturalist uses WGS84.)

Once you have the first label formatted in a way that suits your needs, you can copy and paste all of the formatting from the first label into the remaining labels on your form.

You may edit your label form while in "Preview Results." Any editing you make to the label form in Preview Results will automatically change on the label form. Once you have your label form, you can save it and use it for all labels you wish to print. For each batch of new labels, you need to open the "Mailings" tab, Select Recipients, use an existing list, and choose the file from which you wish to create labels.